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# TORSIONAL RESISTANCE OF MATERIALS DETERMINED BY A NEW APPARATUS WITH AUTOMATIC REGISTRY.

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While the classes of the Stevens' Institute of Technology were recently engaged in their revision of coëfficients, as given by various authorities on strength of materials, the difficulty of determining how far the differences noted were due to errors of observation, and how far to variation in the quality of the materials used, suggested to the writer the advisability of obtaining an apparatus which should make its own record. This could readily be done by so constructing it that a curve might be automatically registered at each tests, which should represent all circumstances of the experiment.

Such an automatic registry would evidently yield more reliable and instructive information in regard to the circumstances of distortion and fracture than could any system of personal observation. Representing the magnitude of the distorting stress at every instant, and under every degree of distortion of the material, up to the limit of elasticity or even to the point of rupture, and exhibiting also the corresponding alteration of form at every point, the pencilled curve would be a record from which might be deduced the coëfficients of elasticity, strength and resilience, as well as the laws governing the relations of the distorting forces to the resistance of the material.

A simple but effective machine was therefore designed and constructed, which accomplishes satisfactorily the desired result, and this machine, as planned by the writer and constructed by Messrs. Hawkins & Wales, instrument makers to the Institute, is shown in Fig. 1.

As here arranged, it is intended for experiments on the torsion of materials. Its modifications, for the purpose of experimenting upon transverse strength, will be described in a subsequent paper, in which will be given the results of that series of experiments.

In the figure, the frame, A A, A′A′, supports two suspended arms, C E, B D, which swing about independent axes in the same line. The arm, B, carries at its extremity a weight, D, and the arm, C, has a handle, E, by which it is moved. The axes of these arms are designed as shown in Fig. 2, each having a rectangular recess at L and at M, which receive each an end of the test piece, which is squared to fit, as shown in Figs. 3 and 4.

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The frame, A'A', carries a guide curve, F, of such form that its ordinates are proportional to the twisting moments exerted by the

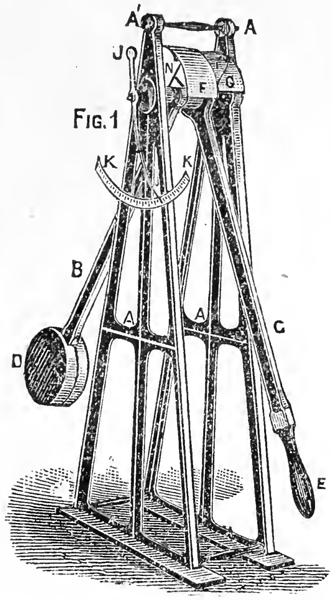



FIG. 1

FIG. 2

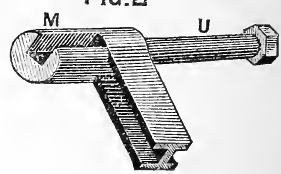



FIG. 3

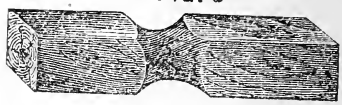
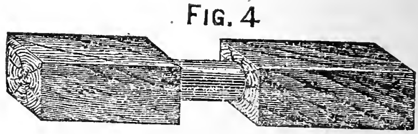


FIG. 4



weighted arm, B D, while swinging through the arc to which the corresponding abscisses are proportional. A pencil holder, I, bears against this guide curve, and, being carried by the weighted arm, is thrown forward, as that arm swings out under the action of the force producing torsion, which force is transmitted through the test piece.

The arm, C E, carries a table, G, and the pencil, I, therefore, traces upon the paper, which is clamped upon it, a curve, the ordinates of which are proportional to the torsional moments, while its abscisses represent the relative motion of the two arms, and, consequently, the amount of torsion to which the test piece has been subjected.

The curves thus described, of which the accompanying plate exhibits a number, present, in a very legible and convenient, as well as reliable, form, all the results of the experiments, of which they are the respective records.

The pointer, J, traversing the arc, K K, is arranged as a maximum hand, and affords a useful check upon the automatic record of maximum strength.

The plate represents the results of average experiments made upon a considerable number of varieties of wood, the test pieces of the form shown in Fig. 3 being used. The diameter of the neck of each piece was seven-eighths ($\frac{7}{8}$) of an inch.

This diameter happened to be that best adapted to use in this machine. A larger size was found, frequently, to yield by the destruction of lateral cohesion, the square head peeling, leaving a prolongation of the cylindrical portion, instead of twisting off in the neck. This size is convenient, also, in consequence of the fact that the coëfficient of ultimate strength for the standard diameter of one inch is obtained, with a close approximation to exactness, by simply multiplying the twisting moment for each piece by 1·5.

These curves exhibit the relative stiffness, strength and resilience of the woods tested very perfectly. The inclination of the straight line, forming the first portion of each diagram, from the vertical is a measue of stiffness; the height of the maximum ordinate indicates the ultimate strength; the point at which deviation from this straight line commences, determines the limit of elasticity, and the area included within each diagram is proportional to the torsional resilience of the test piece.

The fact that the commencement is, in each case, almost a perfectly straight line, is well exhibited in the curve, a a a, of locust, where the horizontal scale is purposely magnified, justifies the usual assumption that, up to the limit of elasticity, Hooke's law is correct, and that the angle of torsion is proportional to the twisting moment.

The short curve of small radius, noticed at the foot of the straight portion of each line, is produced by the slight yielding of the test piece by crushing, where it is grasped by the machine, which yielding continues until a firm hold has been secured.

It will be observed that, in most cases, the torsional resistance increases with the total angle of torsion up to a maximum, then, passing the limit of elasticity, it drops off more or less rapidly, returning finally to zero. In the brittle woods, the fall takes place suddenly, while, in the tougher and more elastic varieties, the resistance decreases very slowly, in some cases vanishing only after the test piece has been twisted through a very large angle.

In the case of black walnut, 6, 6, 6; locust, 11, 11, 11, and, in a still more remarkable manner, in that of hickory, 10, 10, 10, a striking peculiarity is exhibited, which is one of the most interesting and unanticipated developments of this series of experiments. In these

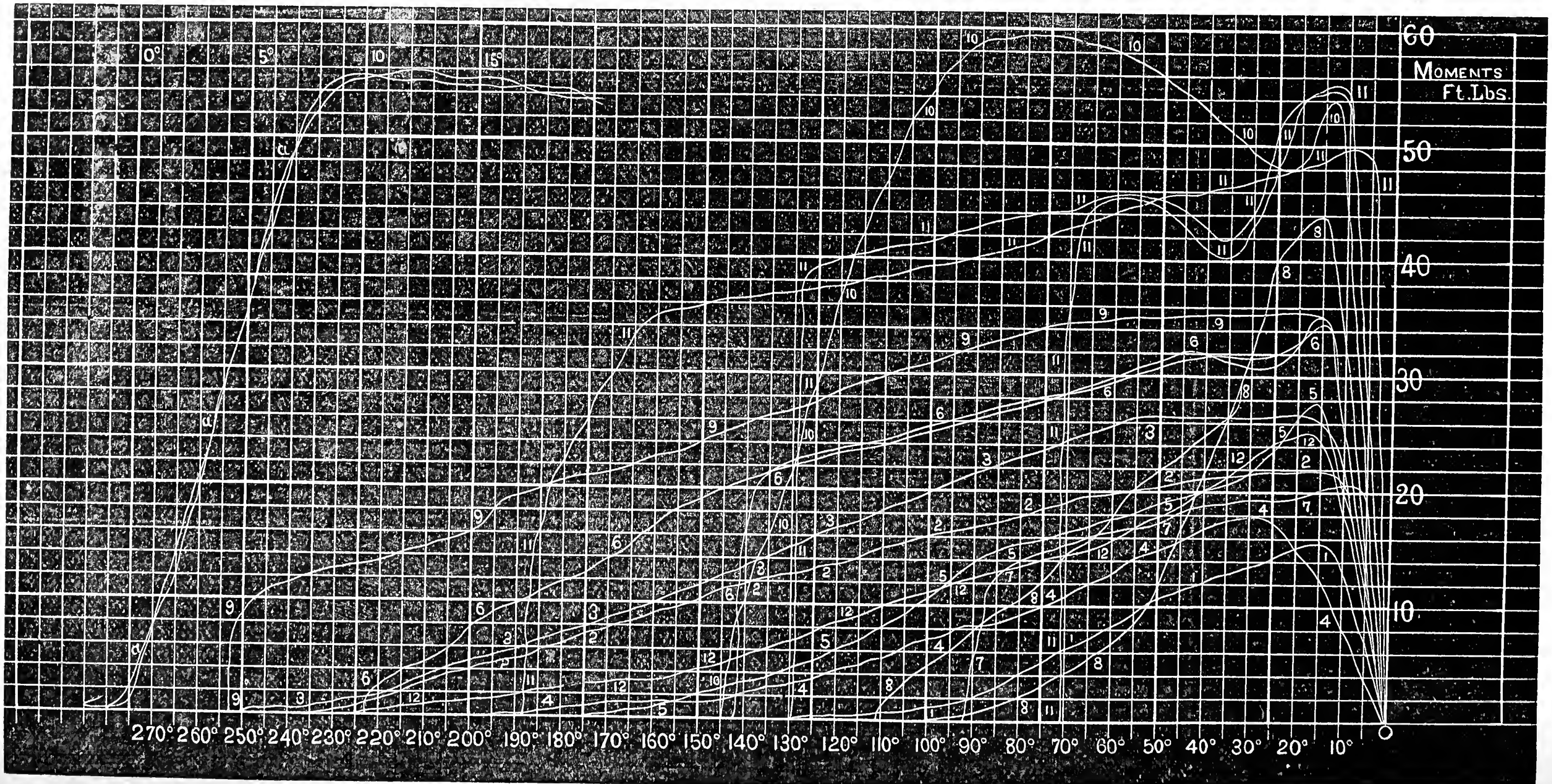
curves the resistance increases with the amount of torsion, until a maximum is reached; the line then drops to a point considerably below, and thence again *rises* and passes another maximum, which, in the case of hickory, is only reached after a torsion of 75°. The resisting moment there becomes considerably greater than at the limit of elasticity.

This striking peculiarity was shown, by carefully repeated experiment, to be due to the fact that, in those woods in which it was noticed, the lateral cohesion seemed much less, in proportion to the longitudinal strength, than in other varieties. Watching the process of yielding under stress, it could be seen, by close observation, that, in the examples now referred to, the first maximum was passed at the instant when, the lateral cohesion of the fibres being overcome, they slipped upon each other, and the bundle of, then, loose fibres readily yielding, the curve dropped until, by lateral crowding, further movement was checked and the resistance again rose until the second maximum was reached. Here yielding again commenced, this time by the breaking of the fibres under longitudinal stress,—under that component of torsional stress which takes a direction parallel with that of the fibres in their new positions. In these cases rupture seems never to occur by true shearing in the transverse plane. The fibres part, one after another, the exterior ones breaking first, under a tensile stress.

The following varieties of wood have been subjected to torsional fracture, and the curves obtained are shown in the plate which illustrates this article:

1. White Pine, (*Pinus strobus.*)
2. S. Yellow Pine (*Pinus australis*), sap wood.
3. " " " " heart wood.
4. Black Spruce (*Abies nigra*).
5. Ash (*Fraxinus Americana*).
6. Black Walnut (*Juglans nigra*).
7. Red Cedar (*Juniperis Virginianus*).
8. Spanish Mahogany (*Swietenia mahogani*).
9. White Oak (*Quercus alba*).
10. Hickory (*Juglans alba*).
11. Locust (*Robinia pseudo-acacia*).
12. Chestnut (*Castanea esca*).

The curves, the *fac similes* of which are given in the plate, exhibit


Moments
Ft. Lbs.
60
50
40
30
20
10
0
10°
20°
30°
40°
50°
60°
70°
80°
90°
100°
110°
120°
130°
140°
150°
160°
170°
180°
190°
200°
210°
220°
230°
240°
250°
260°
270°
0°
5°
10
15°

well the relative values of the materials tested for the various purposes to which they may be applied.

White pine, 1, 1, 1, yields quite rapidly as the torsional moment increases, and the considerable inclination of the line from the vertical indicates its deficiency in stiffness. It soon reaches the limit of elasticity, and the diagram exhibits the maximum strength of the test piece, 15½ foot-pounds. Passing the limit of elasticity and the maximum moment of resistance almost simultaneously, its resisting power decreases rapidly, and with tolerable uniformity, until, at "a total angle of torsion" of 130°, it is twisted completely off. The area comprised within the curve is comparatively small and it is thus shown to have little resilience.

Yellow pine, in accordance with our already well established ideas of its properties, is found by an examination of its curve, 2, 2, 2, 3, 3, 3, to have much greater stiffness, strength and resilience. The sap wood, 2, 2, 2, is equally stiff, in the examples tested, with the heart wood, 3, 3, 3, 3, but sooner passes its limit of elasticity, the former circumstance being quite opposed to the preconceived ideas of the writer. Notwithstanding the comparatively low position occupied by the pines in our list, they are excellent materials, the yellow varieties particularly, for general purposes. Our comparison is made with specimens of equal size, and the important fact of the exceptional lightness of these woods is nowhere brought to our notice by these tests.

Spruce, 4, 4, 4, 4, is less stiff than white pine, even, but possesses greater strength and resilience, its moment of resistance reaching 18 foot-pounds, and twisting through a total angle of torsion of 200°.

Ash, 5, 5, 5, 5, seems to be weaker and less tough than is generally supposed; it is possible that the specimens tested were over seasoned. Its most striking peculiarity is its very rapid loss of strength after passing its limit of elasticity.

Black walnut, 6, 6, 6, 6, of the excellent quality and good condition, as regards seasoning, of the samples tried, is very stiff, strong and resilient, and is but little inferior to oak. Its resisting moment reaches 35 foot-pounds, and one specimen reaches a total angle of torsion of 220°.

Red cedar, 7, 7, 7, 7, is stiff, but brittle, and loses all power of resistance after twisting through an angle of 92°. A torsional moment of 20 foot-pounds only produces a total angle of torsion of 5°.

Spanish mahogany, 8, 8, 8, 8, is very stiff and strong. It is de-

ficient in toughness and resilience, losing its power of resistance very rapidly after passing the limit of elasticity.

White oak, 9, 9, 9, 9, has less torsional strength than either good mahogany, locust or hickory, but is remarkable for its wonderful toughness. It passes its limit of elasticity at 15°, but loses its resisting power very slowly indeed. We find the latter almost unimpaired until it has been subjected to a torsion of 70° ; it only yielded completely at 253°.

Millwrights are evidently perfectly correct in holding this wood in high esteem for strength, toughness and power of resisting heavy shocks and strains.

Hickory, 10, 10, 10, 10, exhibits, in its curve, the remarkable pair of *maxima* already referred to, and has, apparently, the highest ultimate torsional strength, combined with unusual stiffness and considerable resilience. Its moment of resistance to torsion reaches a maximum of 58 foot-pounds.

Locust, 11, 11, 11, 11, has greater stiffness than any other wood in our list, and stands next to hickory in strength ; it is, also, very resilient. Three diagrams are given, each of which possesses its own peculiarities. One specimen is only twisted through a total angle of torsion of 4° by a torsional moment of 48 foot-pounds.

Where more than one curve is given for the same wood, it is a fact worth noticing that the stiffness and ultimate strength are usually very nearly equal, and that the difference between the several specimens becomes marked, if at all, in their degrees of toughness.

In the formula for torsional strength, $Pa = Cd^3$, the curves give, values of C, as follows :

| | | | |
|---|---|---|---|
| 1. White Pine, | 25 | 7. Red Cedar, | 32 |
| 2. Yellow " sap, | 35 | 8. Spanish Mahogany, | 65 |
| 3. " " heart, | 40 | 9. Oak, | 53 |
| 4. Spruce | 30 | 10. Hickory, | 85 |
| 5. Ash, | 43 | 11. Locust, | 80 |
| 6. Black Walnut, | 55 | 12. Chestnut, | 35 |

Determining relative stiffness by obtaining values of the ratio of twisting moment to the total angle of torsion we obtain the following :

| | | | |
|---|---|---|---|
| 1. White Pine, | 1·00 | 7. Red Cedar, | 4·00 |
| 2. Yellow " sap, | 2·25 | 8. Spanish Mahogany, | 3·00 |
| 3. " " heart, | 2·25 | 9. Oak, | 2·53 |
| 4. Spruce, | 0·67 | 10. Hickory, | 4·15 |
| 5. Ash, | 1.87 | 11. Locust, | 5·50 |
| 6 Black Walnut, | 2·63 | 12. Chestnut, | 1·60 |

Taking the well established value for oak as a standard, we deduce the following values for the coëfficient to be used in the formula,

$$\theta = \frac{2\,Pa}{G\pi r^4} = \frac{\text{Total Angle of Torsion.}}{\text{Length of Part Twisted.}}$$

| | | | |
|---|---|---|---|
| 1. White Pine, . . | 220,000 | 7. Red Cedar, . . | 890,000 |
| 2. Yellow " sap, . | 495,000 | 8. Spanish Mahogany, | 660,000 |
| 3. " " heart, . | 495,000 | 9. Oak, . . . | 570,000 |
| 4. Spruce, . . | 211,000 | 10. Hickory, . . | 910,000 |
| 5. Ash, . . . | 410,000 | 11. Locust, . . | 1,225,000 |
| 6. Black Walnut, . | 582,000 | 12. Chestnut, . . | 355,000 |

Finally, by measuring the areas of the several curves, we deduce the following values for relative resilience, white pine being taken as the standard:

The work done in twisting off these specimens is found to have relative values as follows:

| | | | |
|---|---|---|---|
| 1. White Pine, . . | 1·00 | 7. Red Cedar, . . . | 1·61 |
| 2. Yellow " sap, . | 3·01 | 8. Spanish Mahogany, | 2·25; 1·65 |
| 3. " " heart, | 3·87 | 9. Oak, . . . . | 6·60 |
| 4. Spruce, . . | 1·50 | 10. Hickory, . . . | 6·90 |
| 5. Ash, . . . | 2·25 | 11. Locust, . | 7·65; 5·85; 320 |
| 6. Black Walnut, | 5·00; 3·95 | 12. Chestnut, . . . | 2·40 |

The values of coëfficients, as given, will be checked by additional experiments upon test pieces of the form shown in figure 4, carefully turned to a diameter of $\frac{3}{4}$ inch, and of a length, in the neck, of one inch.

Coëfficients for metals will also be given in a later communication.

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